Quaternary Research 84 (2015) 151–158

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Detecting recent changes in the areal extent of North Cascades glaciers, USA

Michael A. O'Neal [a,*], Brian Hanson [b], Sebastian Carisio [b], Ashley Satinsky [b]

[a] *Department of Geological Sciences, University of Delaware, Newark, DE, USA*
[b] *Department of Geography, University of Delaware, Newark, DE, USA*

ARTICLE INFO

Article history:
Received 4 March 2015
Available online 14 July 2015

Keywords:
Glacier
Cascades
Climate change
GIS
Inventory
Global warming

ABSTRACT

We present an exhaustive spatial analysis using the geographic, geometric, and hypsometric characteristics of 742 North Cascades glaciers to evaluate changes in their areal extents over a half-century period. Our results indicate that, contrary to our initial expectations, glacier change throughout the study region cannot be explained readily by correlations in glacier location, size, or shape. Because of the large error attributable to annual variations in glacier area due to snowpack, no statistically reliable change could be detected for 444 glaciers in our study (a slight majority). Of the North Cascades glaciers that do exhibit detectable change, a majority decreased in area, but nevertheless, some were detectably growing. These findings suggest that the integration of weather patterns over time does not neatly translate into correlations with natural variations in the geometry of glaciers. Our statistical analyses of the changes observed indicate that geometric data from a large number of glaciers, as well as a surprisingly large amount of spatial change, are required for a credible statistical detection of glacier-length and area changes over a short (multidecadal) period of time.

Introduction

The North Cascades Range of Washington State represents the most heavily glacierized area in the contiguous United States, where many individual glaciers have become high-profile indicators of regional and global climate change (Dyurgerov and Meier, 2000; Kovanen, 2003; Oerlemans, 2005; Pelto, 2008). Much of the currently available literature discusses North Cascades glaciers in the context of retreat since the recent advances of the 16th to 19th centuries, or annual-to-decadal climate variations that result in substantial shorter-term fluctuations (e.g., Long, 1955; Harrison, 1970; Harper, 1993; Thomas, 1997; O'Neal, 2005). The majority of these analyses rely on a small number of large glaciers with substantial geochronological and historical records (e.g., South Cascade and Easton glaciers).

Previous research of North Cascade glaciers that relied on field-based techniques was limited by the practical sample size of glaciers that could be studied. Alternatively, those studies that are able to combine remotely sensed imagery (multi-temporal airborne and spaceborne imagery) with traditional field-based methods are able to evaluate large populations of glaciers at once, yielding much larger sample sizes, and regional inventories of glacier characteristics (e.g., Meier, 1961; Post et al., 1971). The few available studies that use GIS-based techniques to evaluate North Cascades glaciers have identified changes in termini at both the local and regional scale (Granshaw, 2002; O'Neal, 2005; Granshaw and Fountain, 2006; Satinsky, 2009). A notable effort in this regard is the North Cascade Glacier Climate Project (NCGCP), a comprehensive monitoring project that documents the geometric changes of 47 glaciers since 1984 (Pelto, 1993; Pelto and Riedel, 2001; Pelto, 2008). Other databases, especially GLIMS (Pfeffer et al., 2014), now contain many of these glacier outlines. However, our study specifically attempted to develop data with a one-to-one match for the ice features identified by Post et al. (1971). It is possible that evaluation and matching of different glacier boundaries in other inventories could be used to complete similar analyses with a longer temporal range or a greater spatial scale.

In this study, we evaluate multidecadal changes in the areal extents of glaciers from North Cascades, USA with a threefold purpose. First, we present the geographic, geometric, and hypsometric characteristics of 742 North Cascades glaciers, previously identified in AD 1958 maps and imagery by Post et al. (1971). With these data, we are able to 1) assess the areal changes over a nearly half-century, a period of time during which a global warming signal went from undetectable to unmistakable, and 2) evaluate spatial correlations between the geographic, geometric, and hypsometric variables of individual glaciers and changes in glacial area. Second, we evaluate the sensitivity of our geometric data to important errors inherent to the process of remotely monitoring glacier populations. This includes the spatial error inherent to the imagery used, digitization-operator error, and temporal variations in ice-marginal snow cover, to estimate the threshold required to detect true areal difference—above noise—in glacier geometry change over time. Lastly, we evaluate the sample

* Corresponding author at: Department of Geological Sciences, University of Delaware, Newark, DE 19716.
E-mail addresses: oneal@udel.edu; oneal.michael@gmail.com (M.A. O'Neal).

http://dx.doi.org/10.1016/j.yqres.2015.05.007

sizes needed for detecting significant areal change by treating our dataset as a complete population and subsampling using bootstrap methods.

Methods

Data

Our study area covers a 170 km by 120 km region of heavily glacierized peaks of the North Cascades mountain range in Washington State, from within 2 km of the USA–Canada border to approximately 70 km north of Mount Rainier (Fig. 1). Within the study domain, the areal extents of 742 North Cascades glaciers, geometrically analyzed by Post et al. (1971), were identified and delineated via manual digitization using summertime NAIP orthoimagery from AD 2006, which reports a linear error of 5 m (USDA, 2006, 2009). Aided by a USGS digital raster graphic (DRG) maps and the National Elevation Dataset (NED) data, each glacier's exact location was identified. Boundaries were manually digitized at 1:1,000, a large scale chosen to maximize digitization efficiency without compromising accuracy. Digital orthophoto quarter-quadrangles (DOQQ) of the study area covering the period of AD 1992–1998 (USGS 1982, 1992, 1998) were overlaid to assist in the identification of glacier boundaries. We separated glaciers from the surrounding rocky landscape by identifying breaks in slope, topographic shade and shadows, and visual assessments of debris cover using the NED and DRG data, and aerial imagery. Internal polygons delimiting rock outcrops within the glacier boundary were digitized at a 1:500 scale, and any internal bare rock feature greater than 100 m^2 in extent was excluded from the glacier area calculations. Due to the limitations imposed by the camera angle and resolution of the imagery, it is possible that some debris-covered ice margins were excluded from the glacier area. For direct comparison to the results of Post et al. (1971), areas were rounded to the nearest 0.1 km^2.

A preliminary study by our group (Satinsky, 2009) coupled the aforementioned glacier boundary dataset with the National Elevation Dataset (NED) from the U.S. Geological Survey (USGS), a 30-m digital elevation model (DEM) (Gesch et al., 2002; Gesch, 2007). The resultant dataset was used to evaluate basic planimetric and hypsometric properties of area, perimeter, and minimum and maximum elevation. To refine this preliminary study, we overlaid the digitized AD 2006 glacier boundaries onto a 15-m composite DEM derived from the DEMs produced from summertime ASTER Level 1B orthoimagery between the years

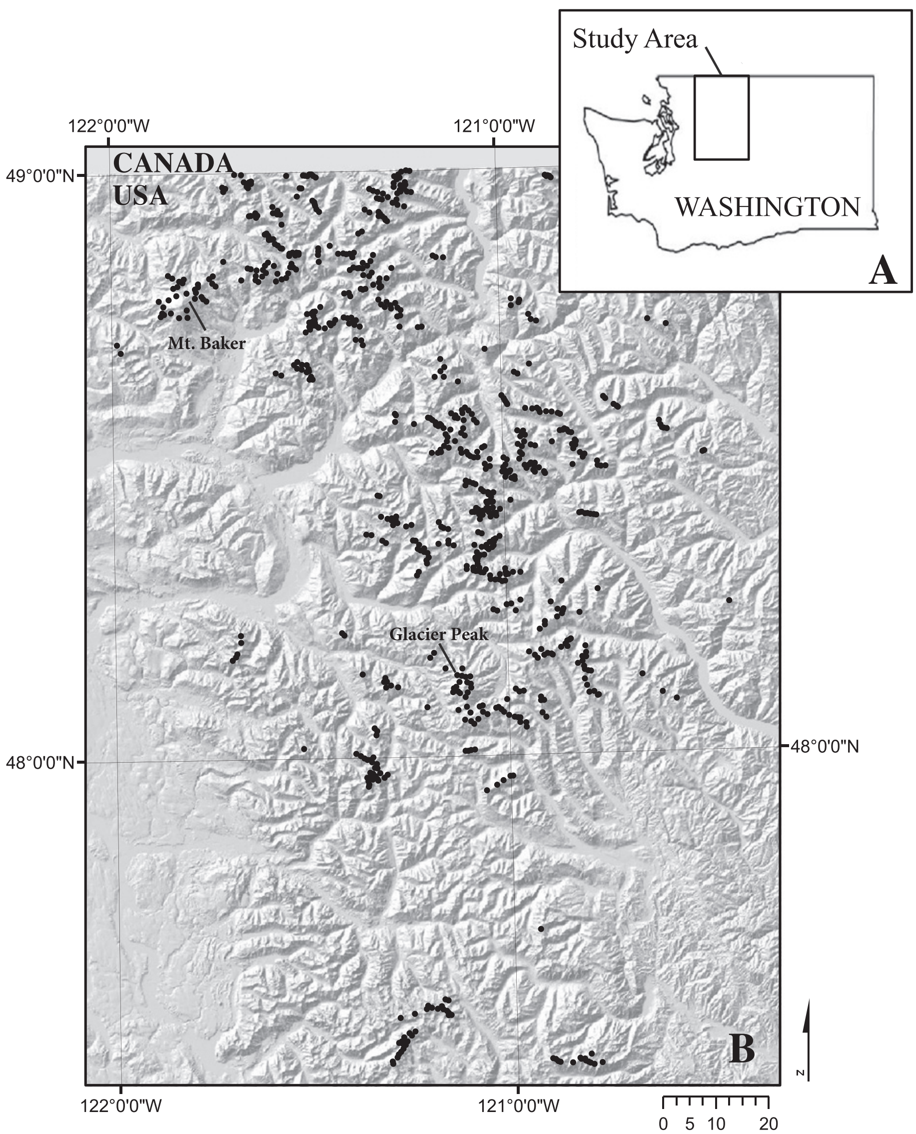

Figure 1. Maps depicting A) the state of Washington with the outlined study area location and B) a shaded relief map of the North Cascades showing the locations of the 742 glaciers included in this study (black circles).

https://doi.org/10.1016/j.yqres.2015.05.007 Published online by Cambridge University Press

AD 2005 and 2007 (Carisio, 2012). The resulting DEM contains values measured within 1 year of the AD 2006 NAIP imagery from which the 742 glaciers were digitized. To explore geographic or topographic controls on the glacier changes in our data set, we performed standard multivariate analyses of 20 ratio-scale variables and one nominal-scale variable developed from the combination of the AD 2006 glacier boundaries and the ASTER DEM. We eliminated two glaciers from univariate statistical analyses because they were essentially small, flat snowbanks in AD 2006 and thus had no elevation-range variables.

The 20 glacier location, size, and morphometric variables, and one nominal-scale variable are as follows: (1) area in AD 1958 (Post et al., 1971) and (2) AD 2006 (Satinsky, 2009), both reported to the nearest 0.1 km^2, along with (3) the absolute and (4) relative difference between those two areas. Variables developed from the 2006 digitized glacier outlines include the coordinates of the centroids in meters of (5) easting and (6) northing within UTM zone 10, and (7) the perimeter length in meters. The remaining variables were calculated from the overlay of the AD 2006 boundaries onto the 15 m DEM, all calculated in meters. Directly from the DEM for each glacier outline, we obtain (8) minimum elevation, (9) maximum elevation, and (10) elevation range. Using the 15 m ASTER DEM elevations that comprise each glacier as individual data points, we calculated the moment statistics: (11) mean, (12) standard deviation, (13) skewness, and (14) kurtosis. The (15) elevation-relief ratio (ERR; Wood and Snell, 1960) was calculated as

$$\mathrm{ERR} = \frac{\bar{z} - z_{\min}}{z_{max} - z_{\min}}$$

We include the ERR as simple topographic descriptor that characterizes each glacier's overall relief regardless of scale. Using the DEM points, (16) equilibrium line altitude (ELA) was calculated artificially from the assumption that 60% of the area of each glacier was in the accumulation area. Once ELA was calculated, (17) an accumulation-area balance ratio (AABR) could be calculated based on the assumption that mass balances are zero at the ELA and increase (decrease) linearly with distance above (below) the ELA. Finally, (18) average slope and aspect (direction of the average slope) were calculated. Because aspect is a modular variable, we separated it into (19) north–south aspect (cosine of aspect azimuth) and (20) east–west aspect (sine of aspect azimuth).

Error analysis

As we analyzed our inventory-scale imagery, we realized the importance of providing comprehensive error metrics that would account for errors intrinsic to the images, introduced by the digitization process, and associated with annual variations in ice-marginal snow cover that affect glacier geometries as they can be perceived in aerial and satellite imagery. Given the methods available to Post et al. (1971), we cannot expect there to be a comprehensive error analysis of this type for the older inventory, so we have to regard it as a static starting point. We are able to express spatial errors for our digitized glacier boundaries as a linear dimension following the methods of Ghilani (2000) and applied to Rocky Mountain glaciers by Hoffman et al. (2007). In what follows, if an estimated glacier area is A, then we can characterize that area by the edge length of a square of the same area, $L = \sqrt{A}$. If we report a linear error, then we are asserting that the glacier area fits in the range $(L - \epsilon)^2 \leq A \leq (L + \epsilon)^2$, and the linear error we report is the value of ϵ.

Manual glacier boundary digitization relies on the accuracy and precision of a trained user in placing vertices along glacier margins. Six different operators with advanced levels of GIS experience were all given the same instructions on identifying glacier boundaries in the orthoimagery. Each digitized the same 25 randomly selected glacier boundaries from the AD 2006 NAIP orthoimagery at a scale of 1:1,000. Area, perimeter length, and the number of vertices for each glacier among the six different datasets were tabulated from the associated database file for every polygon.

Another potential source of error comes from short-term snowpack variability, which could blur glacier margins in the context of a time-series analysis when annual variations are captured by imagery as discrete slices of time. We estimated potential variability in ice marginal snow cover by redigitizing 51 randomly chosen glacier boundaries using summertime NAIP imagery from AD 2009.

Statistical analysis

Finally, multivariate analyses were performed with the primary goal of finding any relationships between the aforementioned variables, but especially to determine if any other variables, such as size, covary with changes in area. Three ratio-scale variables were eliminated from multivariate processing because of intrinsic linearities. Specifically, relative area change and area in AD 1958 were eliminated while area in 2006 and the differences of the two areas were retained, and the local relief was eliminated while retaining the minimum and maximum elevations. A principal components analysis (PCA) was performed using the multivariate variables to identify trends that maximize how much variance is explained with the lowest-numbered vectors. In preliminary versions, a rather large number of variables covary as the area increases or as overall elevation increases, and leaving all of these variables intended to produce overly obvious axes of area and elevation in the 17-dimensional space. The PCA we discuss was performed on a reduced, 12-variable set in an attempt to find sets that would show covariance with AD 1958–2006 changes.

We observed that the distribution of glacier areas in large population such as our inventory is highly skewed towards small glaciers with a small number of large ones (Fig. 2). We thus took advantage of our wealth of glacier data to use bootstrapping resampling methods (Efron, 1981) to examine the reliability of sample size on potential evaluation of glacier changes. Two glaciers that had nearly disappeared in AD 2006 were eliminated from consideration in any statistical comparisons that involved the morphometric variables calculated from the DEM, as most of these variables would have been missing values for a glacier that had no elevation range. Our bootstrapping process began with 5 glaciers and increased in sample size in increments of 5 up to a largest sample size of 740; mean glacier area was calculated for each of 100,000 glacier resamplings. Among the 100,000 samplings at each sample size, percentile values were determined comparable to mean, standard deviation, and two standard deviations. Both the AD 1958 and 2006 inventories were treated in this way. A similar bootstrap analysis was applied to the fractions of the set that were classified as

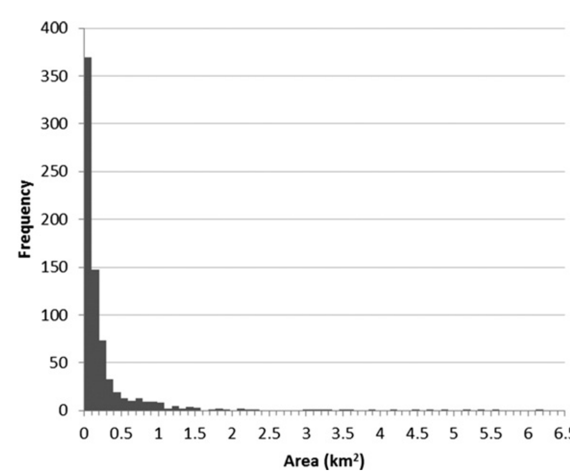

Figure 2. Histogram displaying the frequency distribution of the 742 AD 2006 glacier areas in square kilometers.

https://doi.org/10.1016/j.yqres.2015.05.007 Published online by Cambridge University Press

growing, shrinking, or not changing, as measured between AD 1958 and 2006 imagery.

Because the significance of intervariable correlations depend on assumptions of normality, we also used bootstrap methods to try to identify relationships between glacier areas and area changes, and all of the other geographic, topographic, and morphometric variables that would not show up in correlation statistics but might show up if the values for one variable were stratified by the values of a different variable. The procedure for this was to choose small random samples with replacement from our glacier set, many times over, comparing two of the 17 variables at a time, one of which was either AD 2006 area or the AD 1958–2006 area change and the other was one of the remaining 15 variables. The values from each of the random samples were placed in a two-dimensional bin grid based on the mean of each variable in the sample. If the bin with the maximum number of samples was displaced from the center but off either axis, it would indicate two variables that have some correlation. We carried out this procedure using sample sizes as small as 20 and as large as 200, performing 1 million resamplings for each sample size, binned in an 81 by 81 array.

Results

We first address what contributions various sources of error might have toward our results. We found that manual digitization displayed a relatively small operator error of 7 m. Surprisingly, changes in glacier boundaries resulting from interannual snowpack variability between AD 2006 and 2009 displayed the greatest source of error, showing an areal variation equivalent to a 184 m distance. Combining these two errors with the 5 m reported error of NAIP imagery yields a cumulative linear error metric of 196 m that we use henceforth in our assessment of our glacier inventory. Influenced by our cumulative error metric, we delineated a least conservative (LC) criterion and a most conservative (MC) criterion for determining whether a change detected between the AD 1958 and 2006 inventories represented true change or fell within the inherent error of the inventory process. The LC criterion assumes that the areas presented by Post et al. (1971) were precisely accurate to the 0.1 km^2 used in that report, and accepts as significant all differences between AD 1958 and 2006 that show up at that level of precision. The MC criterion insists that only change above the threshold of our cumulative error metric of 196 m should be counted as significant. We use these criteria as reasonable boundaries for detectable glacier area change.

We next compared glacier areas, both overall and individually, between the AD 1958 and 2006 inventories to evaluate change over time. Using either criterion, between 42% (LC) to 60% (MC) of the glaciers show *no* detectable change over the half-century (Table 1). Using the MC detection criterion, 301 (41%) glaciers show detectable change; 280 glaciers are shrinking in area and 21 are growing. Using the LC criterion, 431 (58%) show detectable change, of which 369 are shrinking and 62 are growing. The mean glacier area among the 742 glaciers remaining was 0.37 km^2 in AD 1958 and 0.31 km^2 in AD 2006 (Table 2). However, we note that between 3% (MC) and 8% (LC) of the glaciers increased in size between AD 1958 and 2006.

Table 1
Numbers of growing, shrinking, and glaciers not changing over the period from 1958 to 2006, using two different measurements of detectability of change. The total number of glaciers in the set is 742.

	Detectability from error analysis		Detectability based on 1958 resolution	
	Number	%	Number	%
Shrinking	280	37.7%	369	49.7%
No change	441	59.4%	311	41.9%
Growing	21	2.8%	62	8.4%

Table 2
Univariate statistics of 20 variables over the 740 glacier set. Note that elevation standard deviation, skewness, and kurtosis are calculated for the gridded elevation points of each glacier, and the univariate statistics about those are calculated over the 740 glacier set, leading to dual use of the statistical terms on some of these. Areas in 1958 were reported to the nearest 0.1 km^2 and are shown with appropriately lower significant figures.

	Mean	S.D.	Min.	Max.	Skew.	Kurtosis
Easting, UTM zone 10 (m)	633576	21187	574949	691111	−0.3	−0.37
Northing (m past 5 million)	370583	41464	259640	429110	−0.81	0.31
2006 Area (km^2)	0.307	0.684	0.0035	6.24	5.2	32
1958 Area (km^2)	0.372	0.725	0.1	7	4.8	28
Mean elevation (m)	2000	245	1150	2770	−0.35	0.13
Minimum elevation (m)	1830	247	1060	2680	−0.18	−0.1
Maximum elevation (m)	2180	297	1250	3280	0.34	1.3
Elevation range (m)	340	250	22	2040	2.7	11.4
Elevation standard deviation (m)	77.1	55.2	6.2	434	2.5	9.4
Elevation skewness	0.11	0.54	−1.6	2.7	0.45	1.6
Elevation kurtosis	2.6	0.92	1.3	12.3	4.5	36.5
ELA (m)	2010	250	1190	2730	−0.33	−0.06
Elevation relief ratio (ERR)	0.478	0.097	0.15	0.77	−0.25	0.17
AABR	0.9	0.48	0.17	5.3	2.6	13
Mean slope (degrees)	24.6	5.6	6.2	43.2	−0.06	0.14
North component of aspect	0.48	0.6	−1	+1	−1.1	−0.03
East component of aspect	0.2	0.61	−1	+1	−0.44	−1
Perimeter (m)	5600	4960	328	35690	2.2	6.4
1958 to 2006 area change (km^2)	−0.067	0.164	−2.3	0.6	−4.5	52
Area change/1958 area	−0.281	0.540	0.0	2.5	0.65	2.2

Analysis of the univariate distributions of each of the 19 continuous variables is presented in Table 2. The North Cascades glacier inventory defies easy characterization as a statistical aggregate. Unexpectedly, our multivariate statistical analysis found that *none* of the variables correlated strongly with areal change (Table 3). We note that glacier areas are extremely positively skewed, in the sense that the great majority of the glaciers are small (Fig. 2); however, the largest glaciers display areas that are several standard deviations larger than the mean. In addition, some variables that we will interpret as shape indicators, such as AABR, are also positively skewed. As calculated from our assumption that the ELA is the point above 60% of the area of each glacier, AABR will be high for glaciers that have steep slopes reaching to high elevations above the ELA, relative to lower slopes below the ELA. In other words, the AABR is high for very concave upward glacier shapes and lower for convex upward glacier shapes. The positive-skewness distribution indicates a preponderance of convex glaciers with a few very concave glaciers. This trend also applies to variables that covary with area, such as elevation range.

A multiple regression comparing the areal change from AD 1958 to 2006 with the 20 variables yielded significant coefficients for easting (+), area in AD 2006 (−), eastward component of aspect (+), north component of aspect (−), and slope (+). Given the preponderance of shrinking or nearly unchanging glaciers, the signs of these coefficients are best interpreted that positive is related to less loss, rather than to growing. Thus, a glacier in our dataset was likely to be more robust (in the sense of losing less area than others) if it was farther east, facing southeast, or with higher slope, and is currently large. However, the adjusted r^2 for the multiple regression between areal change and only the group of statistically significant variables listed was 0.07 indicating that while these relationships have intuitively acceptable directions, they have little to no explanatory value; thus we note these coefficients only as interesting and sensible indications. We wondered whether correlations would be improved given different glacier sample sizes. However, our bootstrap analysis showed that, for samples sizes of 120 glaciers, all the pairs calculated have at least one of the maximum bin positions in the range 38 to 43, indicating that lack of correlation indicated in the standard regression techniques cannot be obviated by intensive resampling.

https://doi.org/10.1016/j.yqres.2015.05.007 Published online by Cambridge University Press

Table 3
Correlation matrix among the 20 variables, expressed as percentages to save space. Only correlations with a magnitude above 20 are shown. Variables are the same variables in the same order as the previous two tables, using abbreviated names. All correlations shown here would be considered statistically significant at a better than 0.01 significance level because of the large sample size.

	East	North	2006 A	1958 A	Mean E	Min E	Max E	E Range	E SD	E Skew	E Kurt	ELA	ERR	AABR	Slope	N Asp	E Asp	Perim	Δ A
North	−45																		
2006 A																			
1958 A			98																
Mean E	48																		
Min E	57	−21	−21		87														
Max E	31		48	47	90	60													
E Range			78	76		−29	57												
E SD			70	68		−28	55	97											
E Skew					−25														
E Kurt										38									
ELA	49		21	21	98	82	90	24	25	−31	−21								
ERR					27		22			−90	−29	32							
AABR										77	39	−23	−65						
Slope							20				−23	22							
N Asp					−21	−23													
E Asp																			
Perim	−24		80	78		−27	44	77	71										
Δ Area				−34															
ΔA/1958 A	−24							33	31									42	46

As a set, the 240 retreating glaciers, identified by our MC detection criterion, display poor correlations among the range of geographic, geometric, and hypsometric variables. However, the 10 growing glaciers identified by our MC detection criterion do display statistically correlated features. Several skewness correlation coefficients are strong within the matrices of the 10 growing glaciers; kurtosis (0.84), ELA (−0.75), ERR (−0.97), and AABR (0.93). Also of note in the growing glaciers is the high correlation coefficient (0.81) between maximum elevation and percent change in glacier area from AD 1958 to AD 2006. Together, these statistics suggest that the 10 growing glaciers have similar geometries with high-altitude accumulation areas.

While the size distribution of glaciers definitely skews towards having a few very large glaciers and many smaller glaciers, we see the population as having a distribution that covers the size range and cannot be characterized by size clusters. A preliminary version of our PCA results indicated that a rather large number of variables covary as the area increases or as overall elevation increases. Inclusion of all variables produced overly obvious axes of area and elevation in the n-dimensional space. Therefore, the PCA we discuss was performed on a reduced variable set in an attempt to find sets that show meaningful covariance with AD 1958–2006 changes. Using the 12 variables presented in Table 4, five principal components showed eigenvalues above 1.0, indicating above-average variance explained (a scree plot of the eigenvalues indicated a noticeable bend after three eigenvalues). Based on the loading shown, we can characterize the first three PCs fairly easily as showing the nature of the covariation among glaciers in our dataset. PC1 we would call shape, loading highly on glaciers that have most of their area at low elevation and a concave upward shape. PC2 is mostly location, loading on the NW/SE trending axis of the Cascades to indicate that glaciers tend to move lower in altitude with higher-latitude locations. PC3 is size and aspect, indicating that small glaciers at high slopes are more likely to be on the north side of the mountain. PC4 is the first component with a strong loading on areal change, and we note its relative independence, loading on different variables than the other significant PCs, except that shrinking glaciers are more likely to be towards the northwest side of the mountain, as noted in the multiple regression.

Lastly, our bootstrapping techniques show that the differences between the areal means of the two inventories are likely to become statistically significant only at a sample size of over 400 glaciers (Fig. 3), representing the crossover point at which the 95% range of one distribution crosses the mean of the other. More precisely, the 2.5% frequency mean of the AD 1958 inventory exceeds the mean of

Table 4
Characteristics of the first five components from a PCA on the 12 listed variables. A scree plot shows a significant break after PC3, but all five components with an eigenvalue above 1.0 were included. Loadings are shown for each of the 12 listed variables, only including loadings with a magnitude above 0.20 for clarity.

	PC1	PC2	PC3	PC4	PC5
Eigenvalue	3.02	1.8	1.33	1.16	1.05
Percentage of variance explained	25.2	15	11.1	9.6	8.7
Northing		0.9			
Easting		−0.67		0.21	0.28
2006 area			−0.64	0.29	
Elevation skewness	0.92				
Elevation kurtosis	0.55		−0.26		
ELA	−0.51	0.57	−0.27		0.36
Elevation–relief ratio	−0.88				
AABR	0.83				
Mean slope	−0.32		0.61		0.31
North component of aspect			0.52	0.59	−0.39
East component of aspect				−0.49	−0.67
1958 to 2006 area change		−0.24	0.32	−0.64	0.3

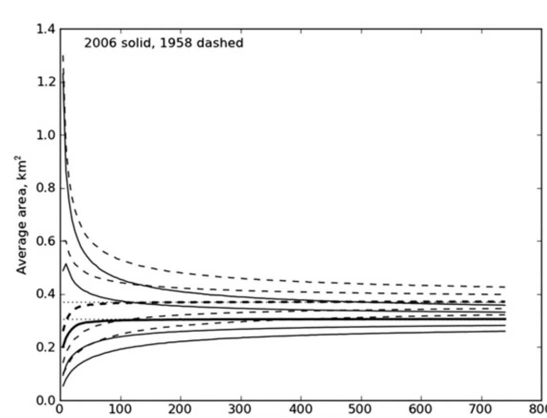

Figure 3. Variation of frequency distribution with sample size for glacier areas. Samples were drawn randomly, with replacement, 100,000 times for each sample size from 5 through 740. The median size for each sample is shown as a heavier curve, with surrounding lighter curves showing sizes whose frequencies are equivalent to 1 and 2 standard deviation ranges. Dotted lines represent the actual means of the complete inventories, with AD 1958 being higher than 2006.

https://doi.org/10.1016/j.yqres.2015.05.007 Published online by Cambridge University Press

Table 5
Bootstrap results for resampling with replacement in sample sizes of 740, with sample sets of 100,000 repeated 100 times. All numbers are reported one significant figure past the point where all 100 sets would agree, with all numbers presented as the bottom of a single unit change in the last digit under random resampling (i.e., the first number could range from 0.322 to 0.323, but not to 0.321).

		N	2.5%	16%	Data mean	Bootstrap median	84%	97.5%
A (km^2)	1958	742	0.322	0.346	0.372	0.371	0.399	0.427
	2006	742	0.259	0.281	0.307	0.306	0.331	0.357
196 m error (%)	Shrinking	280	34.2	36.0	37.7	37.7	39.5	41.2
	No change	441	55.8	57.7	59.4	59.4	61.2	62.9
	Growing	21	1.8	2.2	2.8	2.8	3.4	4.0
0.1 km^2 error (%)	Shrinking	369	46.1	47.8	49.7	49.7	51.5	53.2
	No change	311	38.3	40.0	41.9	41.9	43.7	45.4
	Growing	62	6.5	7.3	8.4	8.4	9.3	10.4

the 2006 inventory at a sample size of 420, and the 97.5% frequency mean of the 2006 inventory drops below the 50% frequency of the 1958 inventory at a sample size of 475. The confidence limits shown for a 742-glacier sample (Table 5) make it clear that any treatment of detectability should find some growing glaciers. However, resampling the glacier population to artificially create smaller inventories, using inventory sample sizes between 5 and 740, increased with replacement by increments of 5 (Fig. 4), shows that finding growing glaciers is not guaranteed for small samples. Using the LC detection criterion, the 95% confidence limit for identifying growing glaciers rises above zero for a sample size of 45, whereas for the MC detection criterion, based mostly on snowpack variability, the required sample size to statistically guarantee finding a growing glacier is 130.

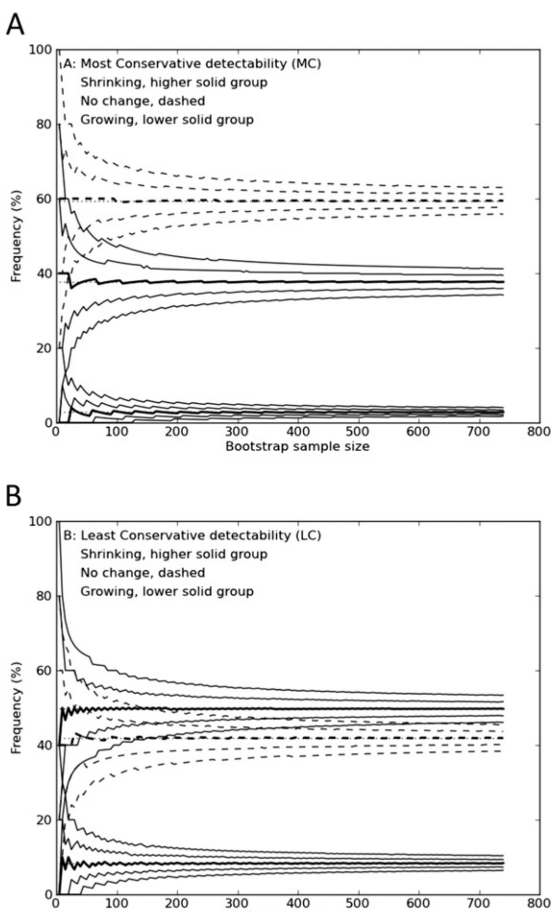

Figure 4. Using a sampling scheme similar to that in Figure 4, the frequencies (as percentage) of growing, shrinking, and unchanging glaciers in each sample were determined, and the median (heavier curve) and 1 and 2 standard deviation ranges of those frequencies are shown. A) Frequencies using the most conservative (MC) change criterion. B) Using the least conservative (LC) change criterion.

We used the same resampling procedures on frequencies of growing, shrinking, or not changing glaciers. We repeatedly took samples of 742 glaciers, with replacement, but noted for each sample only the number of glaciers that had been classified as growing, shrinking, or not changing in the two different classification criteria. The 95% confidence intervals on the shrinking and unchanging glaciers are approximately ±3.5% by either criterion (Table 5). While we assert that more than 60% of the glaciers might be showing no detectable change using the conservative methods described here, there is no reasonable method of pushing that number below 40%. Thus, only with the most liberal definition of detectability along with some statistical variation can one suggest that the majority of the glaciers are shrinking. Similarly, although there is no reasonable statistical treatment to get the proportion of growing glaciers above 10%, there is also no way to say there are no growing glaciers.

Discussion

A careful analysis of glacier change is important in the North Cascades Range of Washington state, where perennial ice is a critical component of the regional hydrologic system. When faced with the atmospheric warming evident over the last few decades, a general trend of reduction in glacier area could affect water resources in many adjacent areas of the Cascades (Tangborn, 1980; Pelto, 1993), as well as hydrologic issues such as sea level rise (Meier, 1984) and sediment transport (Hallet et al., 1996). Paul et al. (2004) emphasizes the importance played even by small glaciers, less than 1 km^2 in area, which as an aggregate, accounts for a significant proportion of ice in a regional glacier population. Heretofore the data used to interpret glacier responses to climate changes in the northern Cascades have been limited, in many circumstances, to only larger glaciers that are readily accessible and have extensive historical records (e.g., Harper, 1993; Kovanen, 2003; Granshaw and Fountain, 2006; Pelto, 2008). Our study aims to present a comprehensive analysis of glaciers over a 50-year time span in the northern Cascades, accounting for changes both in well-studied larger glaciers as well as in many small (>1 km^2) glaciers. Most analyses of North Cascade Glaciers that assess changes on the scale of climate response have far fewer glaciers than ours; we know of no others with a nearly complete population for a region over a nearly half-century duration.

Our study presents a rigorous analysis of areal errors in determining glacier geometric changes in the North Cascades. Though manually laborious, we purposefully chose to develop our dataset via a manual digitization process to minimize errors and maximize resolution. We investigated the use of automated image analysis processes, based on ratio thresholds of various frequency bands, but recognized a tendency for misclassification of snow- and/or debris-covered areas due to their spectral similarity to the surrounding non-glaciated landscape (Paul et al., 2004). Likewise, multispectral imagery, such as Landsat ETM+, chosen for automated detection projects in a glacier inventory of Svartisen (Paul and Andreassen, 2009), or ASTER, used in a glacier inventory of Baffin Island (Paul and Kääb, 2005), has a maximum

https://doi.org/10.1016/j.yqres.2015.05.007 Published online by Cambridge University Press

resolution limit of 10–30 m pixels, too coarse to identify smaller glacial features. At the onset of the study, we assumed that human error during boundary digitization would prove to be a major component of areal error of the end-product inventory. Surprisingly, it proved to be relatively small (i.e., 7 m) among a group of operators who were diverse in terms of training and experience. This measured error may prove a useful metric for inclusion in any study where manual digitizing is necessary.

In contrast to the inherent errors of the remote sensing and manual digitization processes, the largest areal error by far can be attributed to annual snowpack variability, which we measured to be 184 m. Coincidentally, the AD 2006 and 2009 orthoimagery used in this study represents the before-and-after conditions of a significant snowfall event that occurred between AD 2007 and 2008. This result emphasizes the potential magnitude of natural, interannual variation, and underscores the uncertainty in assessing areal changes within a time series of orthoimagery. Snowpack variability error could in theory be systematically reduced by repeated digitizations, such as remeasuring the entire glacier set for AD 2009 and assuming the smallest value of each glacier is a more accurate representation of the area. However, such effort brings obvious difficulties and is simply not practical to perform at an inventory scale.

Given global warming trends over the past half-century, a more striking decrease in glacierized area could have been expected. Trends for the second half of the 20th century indicate that the region we are discussing has experienced both a slight warming and a slight decrease in precipitation (Hartmann et al., 2013). However, we identified only a small overall decrease in average glacier area, from 0.36 m^2 in AD 1958 to 0.31 m^2 in 2006. At the least, our areal change data show that glacier disintegration or segregation is far more common than growth. At most, shrinking areal change could be attributed to long-term decreasing trends in snowpack and possible impacts of anthropogenic warming (O'Neal et al., 2009, 2010; Stoelinga et al., 2010). Roe and O'Neal (2009) emphasized that glacier lengths and areas in the Cascade Range display high variability over time in response to noisy climate forcings due to the array of inherent responses for different glaciers. This is also a climatically complicated area, with Pacific Decadal Variability (Huybers and Roe, 2009; Deser et al., 2012) and significant regional landcover changes (O'Neal et al., 2009, 2010) contributing to the secular climate trends.

We found the North Cascades glacier population difficult to describe cleanly as a statistical aggregate. For example, slope displayed a weak correlation with areal change in the 742 Cascade glaciers, in contrast to the findings of Hoelzle et al. (2003) that slope exerted a predominant influence on the mass loss of glaciers over decadal to century time scales in 68 glaciers in the Swiss Alps, with steeper sloping glaciers exhibiting the least negative mass balances. We found that a dominant majority (586 out of 742) of the entire glacier set displayed an average north aspect, in contradiction to expectations of orographically controlled accumulation on the southwestern and western flanks as weather systems cross the range. More importantly, the 68.6% of the glaciers in north-facing quadrants are, in part, within areas where one would expect the effects of rain shadows to have negative impacts on glacier mass balance. Thus, our inventory data suggest that topographic shade promotes preservation (e.g., Evans and Cox, 2005), without regard to the amount of annual precipitation received.

Because glacier growth shows no consistent correlation with either slope or aspect, our data suggest that North Cascade glaciers are responding more to local physiographic settings and microclimate processes (e.g., Hodge et al., 1998; O'Neal et al., 2009, 2010) than to physiographic setting or large circulation patterns in the Pacific Ocean basin. This suggestion is further supported by the fact that the 240 shrinking glaciers, identified by our MC detection criterion, display poor correlations among the range of geographic, geometric, and hypsometric variables. As noted by Braithwaite (2009), the accumulation of glacier mass balance and change data over the past half century has not created as much insight as we would have hoped. Even with a very rich dataset such as developed here, explanations of why some glaciers grow and others shrink can be elusive.

Lastly, we found that the largest North Cascade glaciers that have been used in many previous studies to interpret the behavior of the larger population (Pelto, 1993; McCabe and Fountain, 1995) display characteristics that flag them as outliers with respect to the overall glacier inventory. Together, the largest 10 glaciers have areal changes that range from −44% to +100%, and, in comparison to the average of glaciers in the inventory, are significantly larger in area, extend to higher and lower elevations, are lower in slope, and are longer (Carisio, 2012). The most studied of these glaciers is South Cascade Glacier, identified by the United States Geological Survey (USGS) as the "benchmark" glacier of the North Cascades range due to its relative accessibility and continuous record since the year 1958 (Fountain et al., 1997; Oerlemans, 2005; USGS, 2007); however, it is 533% larger, 35% longer, 150% flatter, and shrank 6% more than the average North Cascade glacier between AD 1958 and 2006. Some of these North Cascades glaciers, such as Easton and Lyman, have been used as indicators of both regional and global climate change (Kovanen, 2003; Oerlemans, 2005; Pelto, 2008). However, we find that these well-studied glaciers do not well represent the study population, suggesting that caution should be taken when extrapolating data gathered from these outlier glaciers to the larger North Cascades glacier population, or to glaciers in a global sense.

Perhaps the clearest message of our results is that the regional climate forcing cannot be guaranteed to affect any individual glacier and that a large sample of glaciers may be necessary for understanding regional glacier volume changes. Although our analysis is restricted to the glaciers in the northern Cascades Range, our methods and results can be used to assess the number of glaciers needed on any spatial or temporal scale where glaciers are expected to have responded to a detectable regional or global forcing. Although we cannot say for certain how many glaciers may be needed to properly assess regional variations outside our study area, our resampling calculations suggest that reliance on very small samples or "indicator" glaciers is unlikely to produce reliable results.

References

Braithwaite, R.J., 2009. After six decades of monitoring glacier mass balance we still need data but it should be richer data. Annals of Glaciology 50 (50), 191–197.

Carisio, S.P., 2012. Evaluating Areal Errors in Northern Cascades Glacier Inventories (M.S. Thesis), Department of Geography, University of Delaware (71 pp.).

Deser, C., Phillips, A.S., Tomas, Ro.A., Okumura, Y.M., Alexander, M.A., Capotondi, A., SCott, J.D., Kwon, Y.-O., Ohba, M., 2012. ENSO and pacific decadal variability in the Community Climate System Model Version 4. Journal of Climate 25 (8), 2622–2651.

Dyurgerov, M.B., Meier, M.F., 2000. Twentieth century climate change: evidence from small glaciers. Proceedings of the National Academy of Sciences of the United States of America (PNAS) 97, 1406–1411.

Efron, B., 1981. Nonparametric estimates of standard error: the jackknife, the bootstrap and other methods. Biometrika 68 (3), 589–599.

Evans, I.S., Cox, N.J., 2005. Global variations in local asymmetry in glacier altitude: separation of north-south and east-west components. Journal of Glaciology 51, 469–482.

Fountain, A.G., Krimmel, R.M., Trabant, D.C., 1997. A strategy for monitoring glaciers. 1132. U.S. Geological Survey Circular, p. 19.

Gesch, D.B., 2007. The National Elevation Dataset. In: Maune, D. (Ed.), Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 99–118.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., Tyler, D., 2002. The National Elevation Dataset. Photogrammetric Engineering and Remote Sensing 68 (1), 5–11.

Ghilani, C.D., 2000. Demystifying area uncertainty: more or less. Vol. 60. Surveying and Land Information Systems, pp. 177–182.

Granshaw, F., 2002. Glacier Change in the North Cascades National Park Complex, Washington State USA, 1958-1999 (Master's thesis), Retrieved from Glacier Research at Portland State University, Portland, OR (134 pp.).

Granshaw, F.D., Fountain, A.G., 2006. Glacier change (1958-1998) in the North Cascades National Park Complex, Washington, USA. Journal of Glaciology 52, 251–256.

Hallet, B., Hunter, L., Bogen, J., 1996. Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. Global and Planetary Change 12, 213–235.

Harper, J.T., 1993. Glacier terminus fluctuations on Mount Baker, Washington, U.S.A., 1940–1990, and climatic variations. Arctic and Alpine Research 25, 332–340.
Harrison, A.E., 1970. Fluctuations of Coleman Glacier, Mt Baker, Washington, U.S.A. Journal of Glaciology 9, 393–396.
Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M., Zhai, P.M., 2013. Observations: Atmosphere and surface. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Hodge, S.M., Trabant, D.C., Krimmel, R.M., Heinrichs, T.A., March, R.S., Josberger, E.G., 1998. Climate variations and changes in mass of three glaciers in Western North America. Journal of Climate 11, 2161–2179.
Hoelzle, M., Haeberli, W., Dischl, M., Peschke, W., 2003. Secular glacier mass balances derived from cumulative glacier length changes. Global and Planetary Change 36, 295–306.
Hoffman, M.J., Fountain, A.G., Achuff, J.M., 2007. 20th-century variations in area of cirque glaciers and glacierets, Rocky Mountain National Park, Rocky Mountains, Colorado, USA. Annals of Glaciology 46 (1), 349–354.
Huybers, K., Roe, G.H., 2009. Spatial patterns of glaciers in response to spatial patterns in regional climate. Journal of Climate 22 (17), 4606–4620.
Kovanen, D.J., 2003. Decadal variability in climate and glacier fluctuations on Mt. Baker, Washington, USA. Geografiska Annaler 85A, 43–55.
Long, W.A., 1955. What's happening to our glaciers. The Scientific Monthly 81, 57–64.
McCabe, G.J., Fountain, A.G., 1995. Relations between atmospheric circulation and mass balance of South Cascade Glacier, Washington, U.S.A. Arctic and Alpine Research 27, 226–233.
Meier, M.F., 1961. Distribution and variations of glaciers in the United States exclusive of Alaska. General Assembly of Helsinki, July 25-August 6, 1960, Snow and Ice Commission. 54. International Association for Scientific Hydrology, Publication, pp. 420–429.
Meier, M.F., 1984. Contribution of small glaciers to global sea-level. Science 226, 1418–1421.
O'Neal, M.A., 2005. Late little ice age glacier fluctuations in the Cascade Range of Washington and northern Oregon (Ph. D. dissertation). Retrieved from Earth and Space Sciences at University of Washington, Seattle, WA. (UMI No. 3178155), 116 pages
Oerlemans, J., 2005. Extracting a climate signal from 169 glacier records. Science 308, 675–677.
O'Neal, M.A., Hanson, B., Leathers, D.J., Goldstein, A., 2009. Estimating landcover-induced increases in daytime summer temperatures near Mt. Adams, Washington. Physical Geography 30, 130–143.
O'Neal, M.A., Roth, L.B., Hanson, B., Leathers, D.J., 2010. A field-based model of the effects of landcover changes on daytime summer temperatures in the North Cascades. Physical Geography 31 (2), 137–155.
Paul, F., Andreassen, M., 2009. A new glacier inventory for the Svartisen region, Norway, from Landsat ETM+ data: challenges and change assessment. Journal of Glaciology 55 (192), 607–618.
Paul, F., Kääb, A., 2005. Perspectives on the production of a glacier inventory from multispectral satellite data in Arctic Canada: Cumberland Peninsula, Baffin Island. Annals of Glaciology 42 (1), 59–66.
Paul, F., Kääb, A., Maisch, M., Kellenberger, T., Haeberli, W., 2004. Rapid disintegration of Alpine glaciers observed with satellite data. Geophysical Research Letters 31.
Pelto, M.S., 1993. Current behavior of glaciers in the North Cascades and its effect on regional water supply. Washington Geology 21, 3–10.
Pelto, M.S., 2008. Impact of climate change on North Cascade Alpine Glaciers, and Alpine Runoff. Northwest Science 82 (1), 65–75.
Pelto, M.S., Riedel, J., 2001. Spatial and temporal variations in annual balance of North Cascade glaciers, Washington 1984–2000. Hydrological Processes 15, 3461–3472.
Pfeffer, W.T., Arendt, A.A., Bliss, A., Bolch, T., Cogley, J.G., Gardner, A.S., Hagen, J.O., Hock, R., Kaser, G., Kienholz, C., Miles, E.S., Moholdt, G., Mölg, N., Paul, F., Radić, V., Rastner, P., Raup, B.H., Rich, J., Sharp, M.J., and the Randolph Consortium, 2014. The Randolph Glacier Inventory: a globally complete inventory of glaciers. Journal of Glaciology 60 (221), 537–552.
Post, A., Richardson, D., Tangborn, W.V., Rosselot, F.L., 1971. Inventory of glaciers in the North Cascades Washington. Professional Paper 705-A. US Geological Survey (19 pp.).
Roe, G., O'Neal, M.A., 2009. The response of glaciers to intrinsic climate variability: observations and models of late Holocene variations in the Pacific Northwest. Journal of Glaciology 155 (193), 839–854.
Satinsky, A.M., 2009. Geometric changes of 742 North Cascade glaciers derived from 1958 and 2006 aerial imagery (Master's thesis), University of Delaware, Newark, DE (UMI No. 1469516, 69 pp.).
Stoelinga, M.T., Albright, M.D., Mass, M.D., 2010. A new look at snowpack trends in the Cascade Mountains. Journal of Climate 23, 2473–2491.
Tangborn, W.V., 1980. 2 models for estimating climate-glacier relationships in the North Cascades, Washington, USA. Journal of Glaciology 25 (91), 3–21.
Thomas, P.A., 1997, Mt. Baker Glaciation. Unpublished Thesis, Western Washington University.
USDA, 2006 and 2009. National Agriculture Imagery Program (NAIP). Farm Service Agency. Washington State Aerial Imagery.
USGS., 1982-1998, 2007. Digital Raster Graphics. Washington State. USGS., Digital Orthophoto Quadrangles and Quarter-Quadrangles. Washington State. USGS. In: March, R. (Ed.), Glacier Mass Balance Summary (http://ak.water.usgs.gov/glaciology/all_bmg/3glacier_balance.html).
Wood, W.F., Snell, J.B., 1960. A Quantitative System for Classifying Landforms. Quartermaster Research & Engineering Command, U.S. Army Technical Report, EP-124.